Fabric Structure Strain Monitoring System

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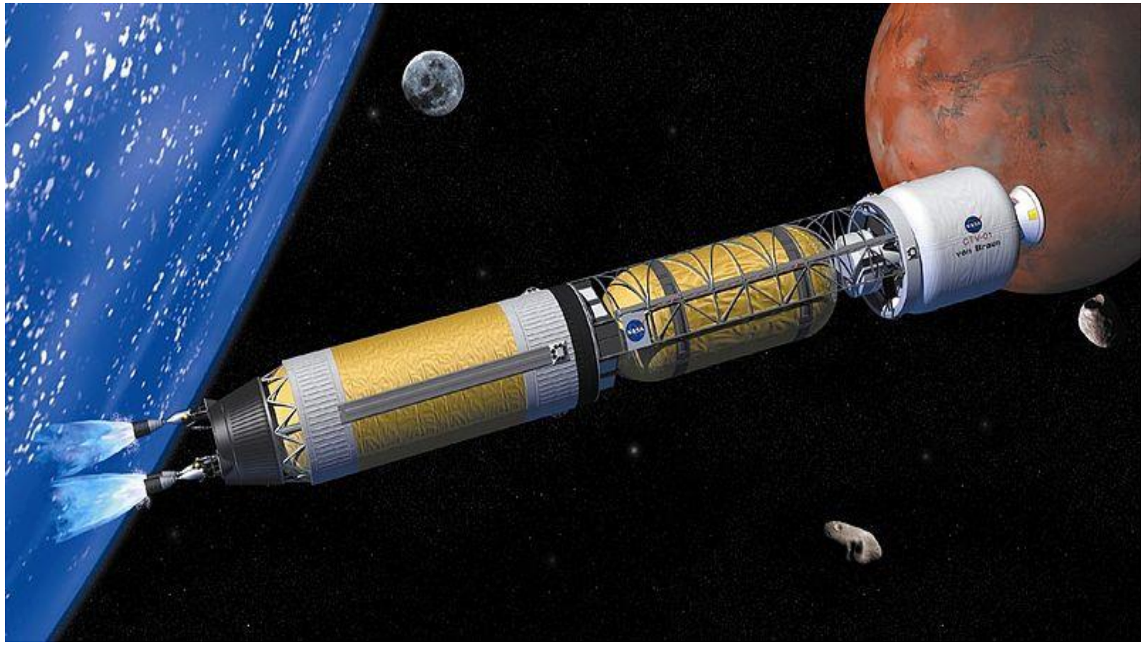
Lightweight Structures at NASA

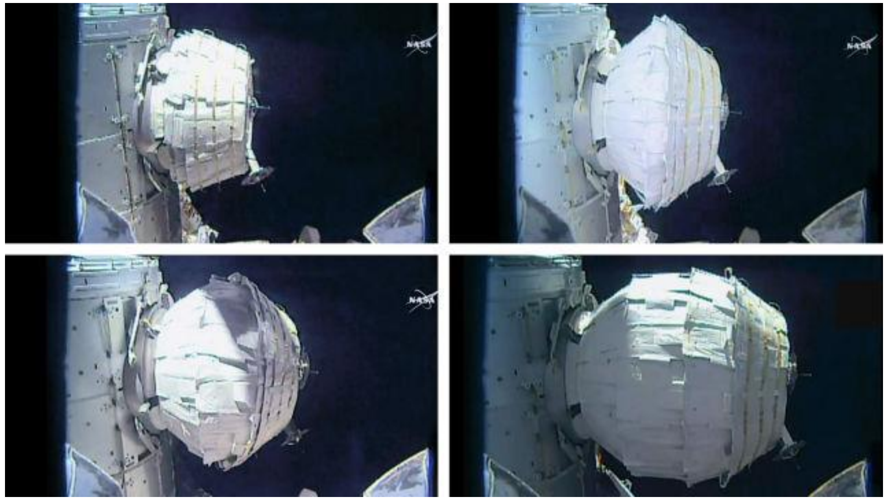
- One of the biggest hurdles for NASA's deep space goals is the size and mass of future manned vehicles and habitats
- Lightweight structures are needed to provide significant mass and volume savings
- Typically composites and fabric based structures
  - Carbon fiber based pressure vessels
  - Multi-functional sandwich structure
  - Inflatable habitats/airlocks



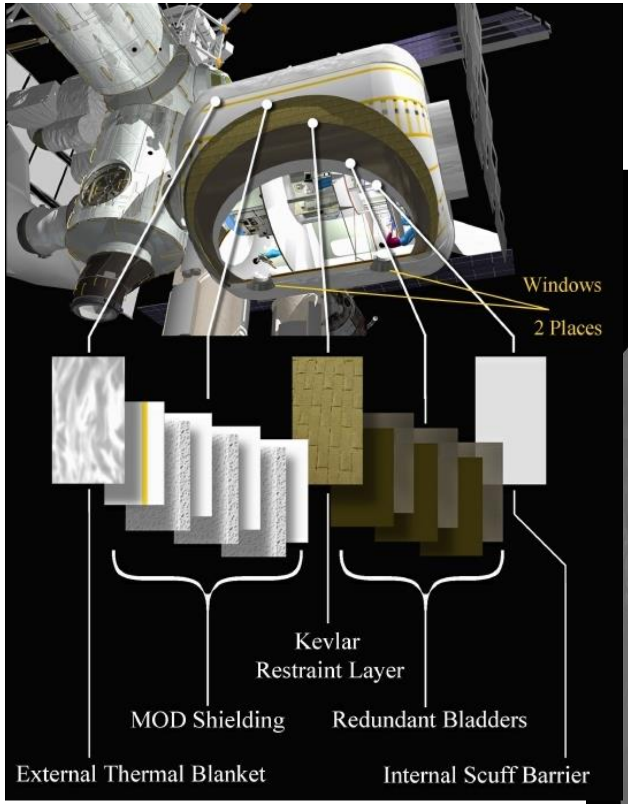
Conceptual NASA Transit Vehicle with Inflatable Habitat

Inflatable Habitat Examples

- Inflatable habitats are fabric based pressure vessels
- Composed of multiple layers of different materials for structure, pressure, MMOD and thermal considerations
- Fabric layers can be packed tightly for launch and expanded in orbit, providing significant volume savings
- BEAM size module provides ~75% volume savings compared to similar sized metallic structure



BEAM Expansion on ISS

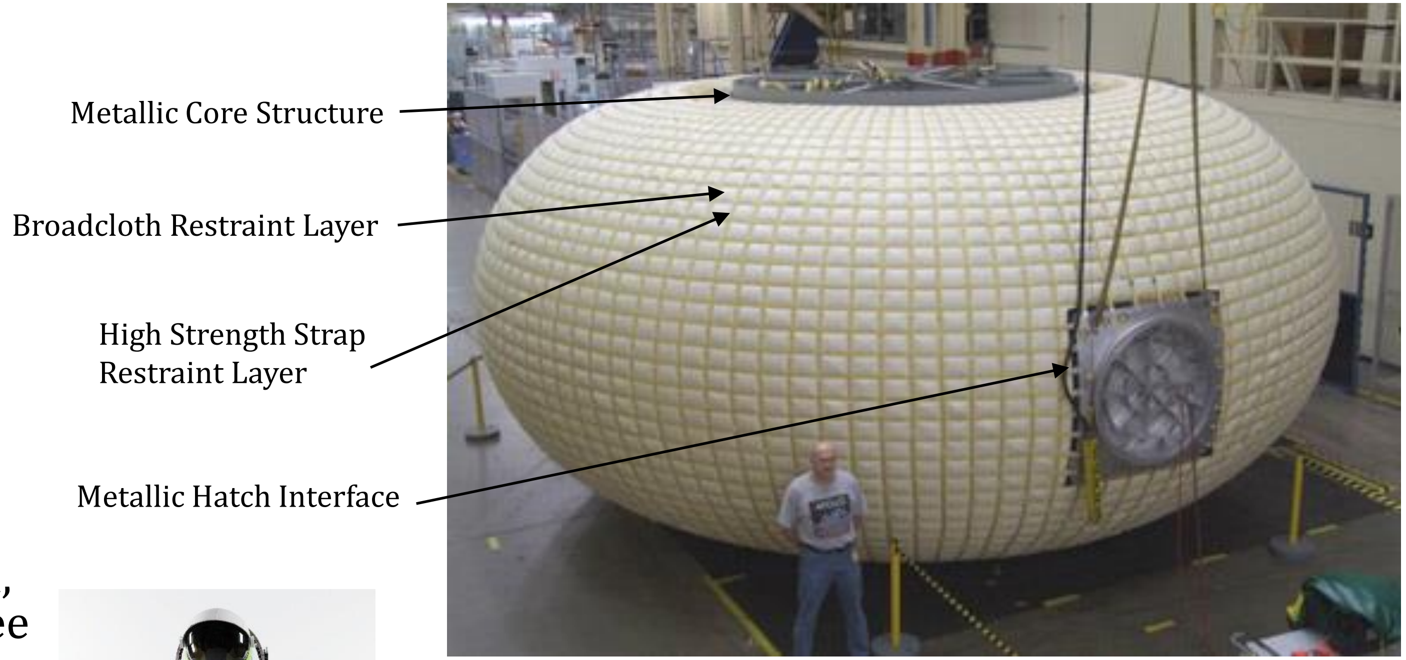


TransHAB Layer Descriptions

TransHAB Cutaway View

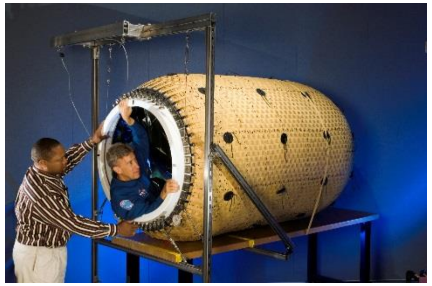
Inflatable Habitat Examples

- Inflatable structures can be used for a variety of applications and designs:
  - Lunar/Mars habitat
  - Airlock
  - Hyperbaric Chamber
  - Spacesuits
- Composed of two primary layers:
  - Pressure/bladder layer – holds the internal pressure
  - Restraint layer – structural layer, take loads from pressure layer and external forces
- Restraint layer is often made of broadcloth, cordage, straps or a combination of all three
- Habitat often has metallic or composite components to take launch loads or rigid interfaces (hatches, windows, etc) – not completely lightweight

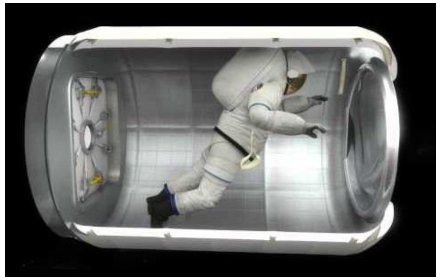


JSC Inflatable Lunar Habitat

NASA Z-2 Spacesuit



JSC Inflatable Hyperbaric Chamber



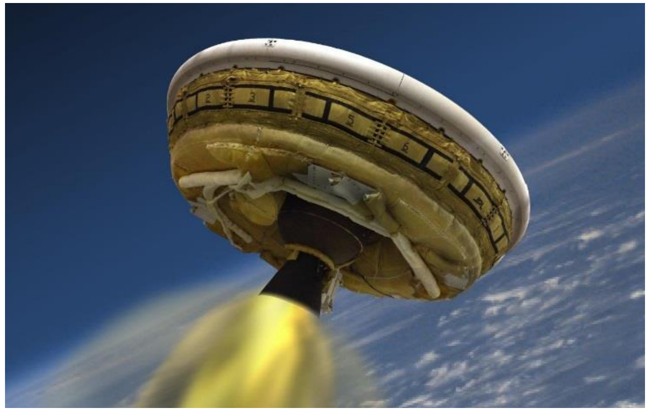
NASA Inflatable Airlock Concept

Fabric Decelerator Examples

- Current work to use inflatable and expandable heat shield systems for Mars landing
  - HIAD (Hypersonic Inflatable Aerodynamic Decelerator)
  - LDSD (Low-Density Supersonic Decelerator)
- These systems have similar structure to inflatable habitats with an internal pressure vessel and restraint layer of cloth, straps and cords
- Still use metallic components for interfaces – not completely lightweight

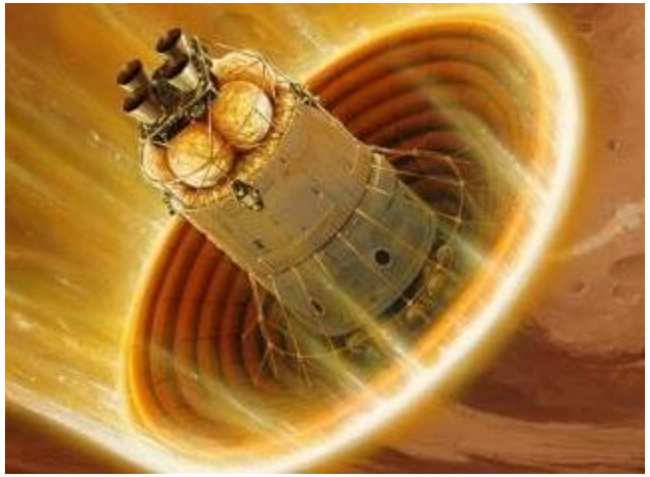
- **Fabrics are an emerging technology for space structures and have a bright future for NASA**

LDSD Flight Test Article



LDSD Flight Test Artist Rendering

HIAD Structural Layer



HIAD In-flight Artist Rendering

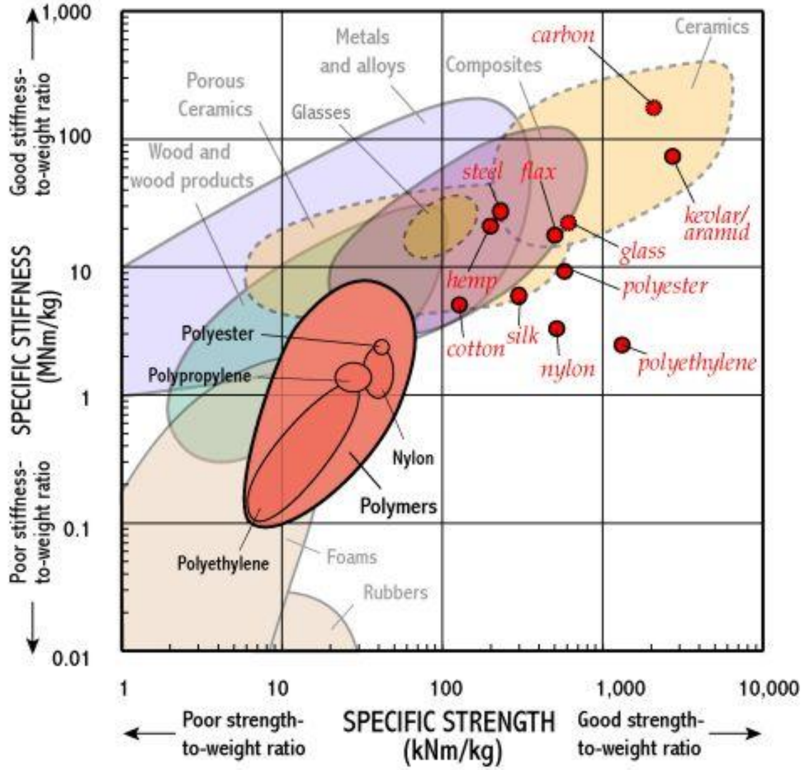
Fabrics vs. Metals

- High strength fabrics are used for their excellent strength-to-weight ratio
- High fiber strength with low density
- Broadcloth, straps, and cordage are made of fibers either twisted or woven together
- Fabric materials are not isotropic and do not behave regularly like metals
- Lack of manufacturing standards and knowledge of stress state create a wide range of material properties for fabrics
- Leads to a NASA required design factor of safety of **6** and often an inefficient and over-conservative design

- **Increased desire for better strain monitoring techniques to evaluate performance of fabric structures**

	Young's modulus (GPa)	Density (kg/m^3)	Strength (MPa)
Cotton	7.9	1,540	225
Hemp	32	1,490	300
Bulk Polyester	2.9	1,300	50
Bulk Nylon	2.5	1,090	63
Carbon Fiber	300	1,770	3,430
Aramid Fiber	**124**	**1,450**	**3,930**
Polyester Fiber	13.2	1,390	784
Nylon Fiber	3.9	1,140	616
Alloy Steel	**210**	**7,800**	**1,330**

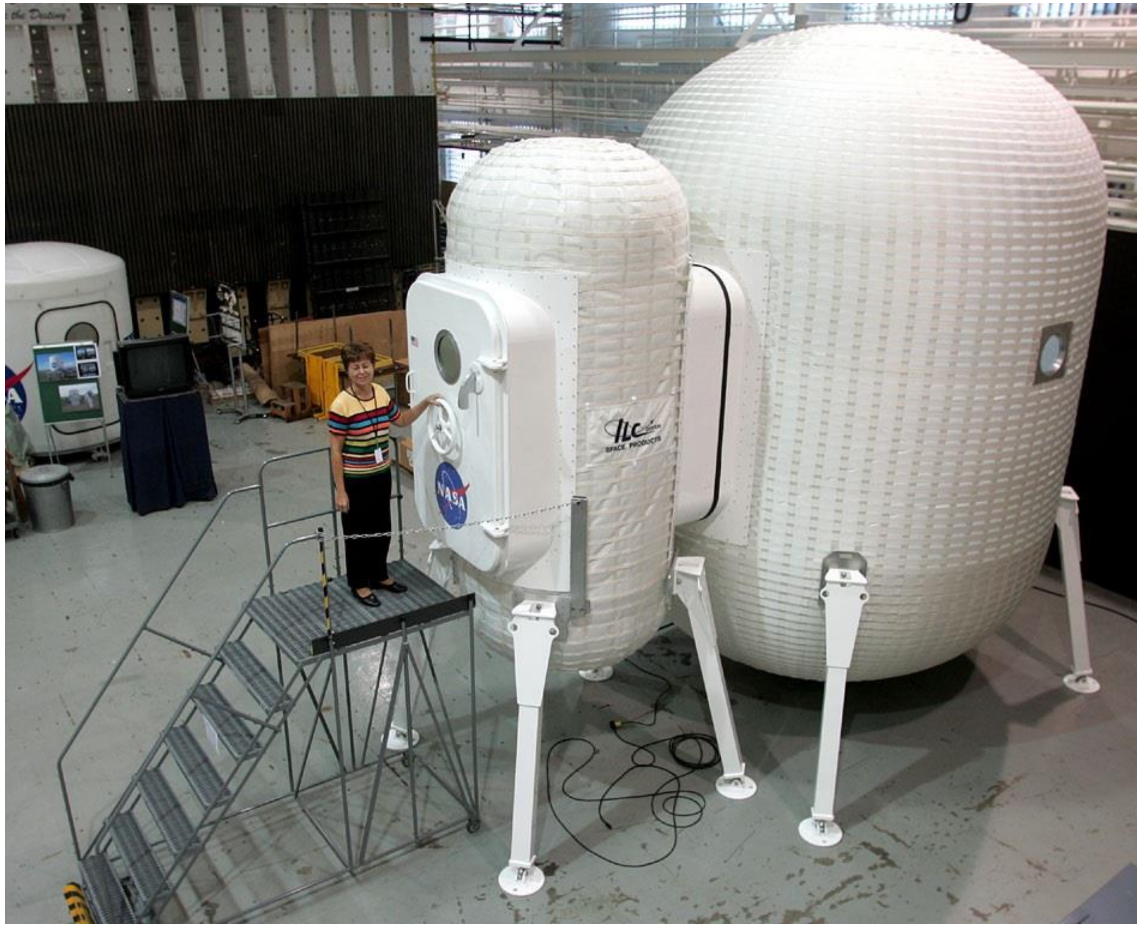
Material Property Comparison Table
(Credit: University of Cambridge)



Material Selection Plot
(Credit: University of Cambridge)

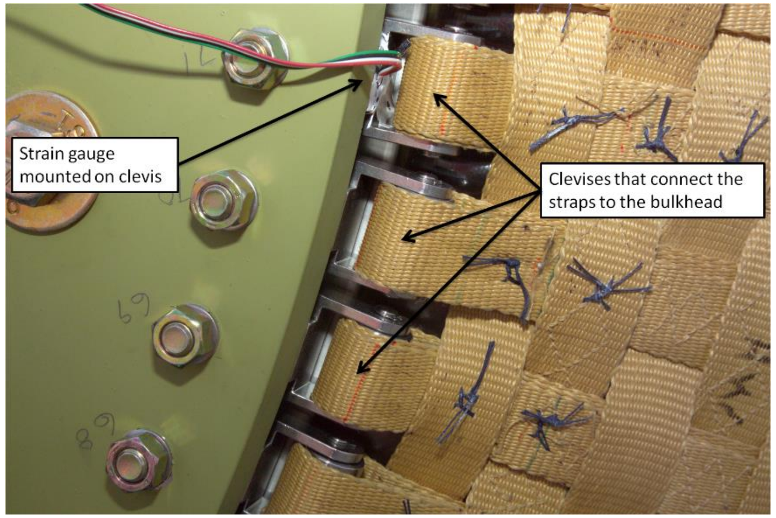
Fabric Structure Strain Measurements

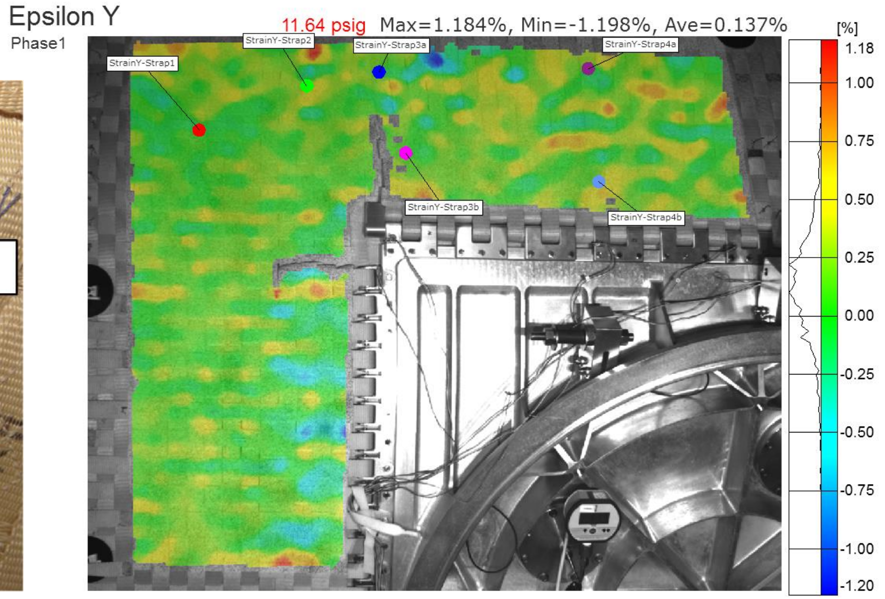
- Important considerations for a strain measuring device:
  - Measure and stretch to high strains (10-50%)
  - Measure and withstand peak loads during dynamic loading
  - Measure stationary loads over extended periods of time without the loss of signal/creep
  - Ability to be ruggedly adhered to or integrated with a textile and staying fixed during the entire lifetime of the vehicle or test
  - Ability to be integrated with the textile such that it can be packaged and limit snag hazards or interference with other components
- Traditional strain gauges and metallic devices do not work on flexible materials
- **New technologies need to be sourced and developed for accurate fabric strain monitoring**

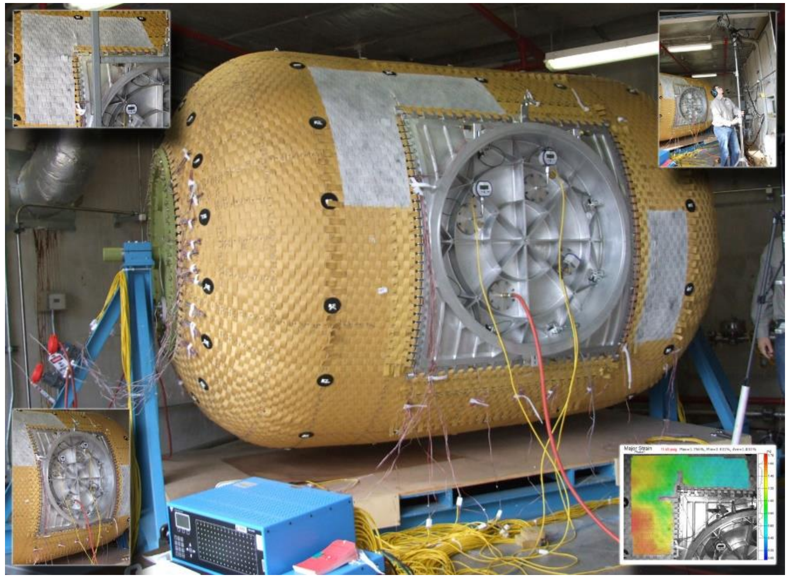

LaRC Inflatable Habitat

Inflatable Habitat Strain Measurements

- Current strain monitoring techniques for inflatable structures utilize optical measurement systems
- Traditional foil strain gauges are used on metallic components
- Photogrammetry/digital image correlation (DIC) uses a dual camera system and speckle pattern to measure the strain on the fabric restraint layer
- DIC system is accurate and provides good results, but limited to a small surface area
- DIC system only works for ground tests when the restraint layer is visible, it does not work in space environment with MMOD and thermal layers







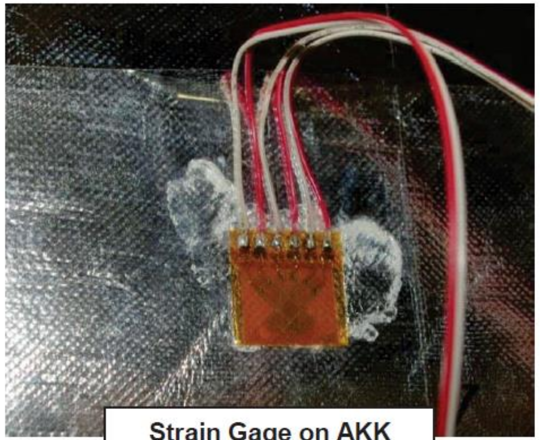
(D. Litteken et al, 2012, AIAA Structures)

HIAD Strain Measurements

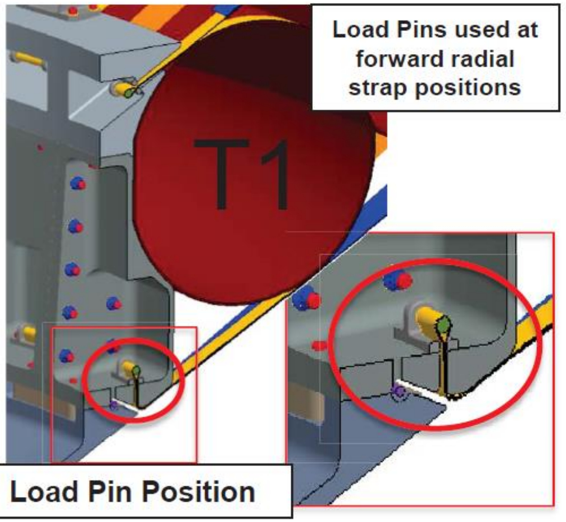
- HIAD structure made of series of pressurized torus' held together with system of straps
- Uses metallic load pins at strap to metal interface and strap tension gauges in-line with straps
- Foil strain gauges epoxied to pressurized torus surface


Strap Load Pin

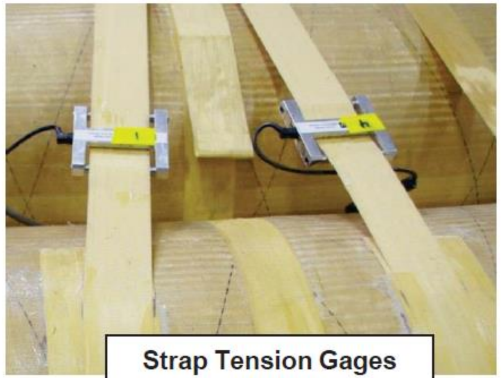
Strap Tension Gage

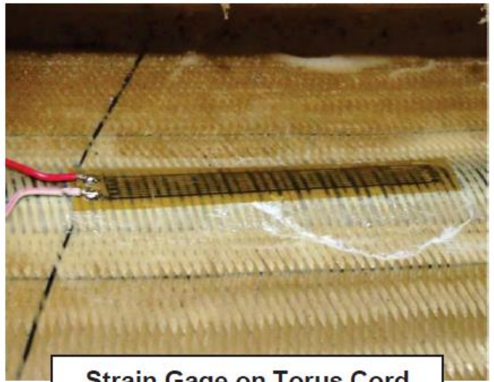

Strain Gage on AKK


6m HIAD Inflatable Structure Before Testing



Load Pin Position


Strap Tension Gages on Crow's Feet Straps


Strain Gage on Torus Cord

Also Used: String Pots, Manometer, Pressure Transducers, Ram Loadcell

(G. Swanson et al, 2014, International Planetary Probe Workshop)

Parallels to Parachutes

- Parachutes are the most commonly used fabric structure for space applications
- Similar restraint layer design as inflatables
- **In need of similar strain measuring systems**

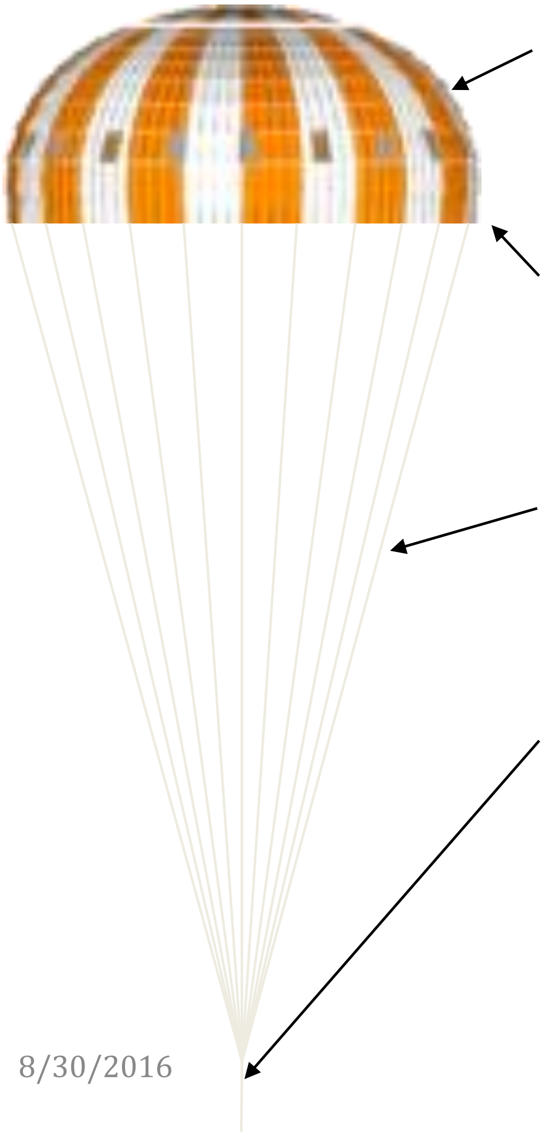
Inflatables

- Inflates with internal pressure
- Structural design uses a system of high strength straps and broadcloth
- Packaged for extended period of time before deployment
- Dynamic loading during deployment, then steady-state loads over extended lifetime
- 1-5 year performance life

Parachutes

- Deploys with external air pressure
- Structural design uses a system of high strength cords and a canopy broadcloth
- Packaged for extended period of time before deployment
- Extreme and dynamic loading during deployment, then steady-state loads over short lifetime
- 5-20 min performance life

Parachute Structure



Canopy

- Carries air pressure load, distributes load to suspension lines
- Broadcloth, woven material

Reefing Line

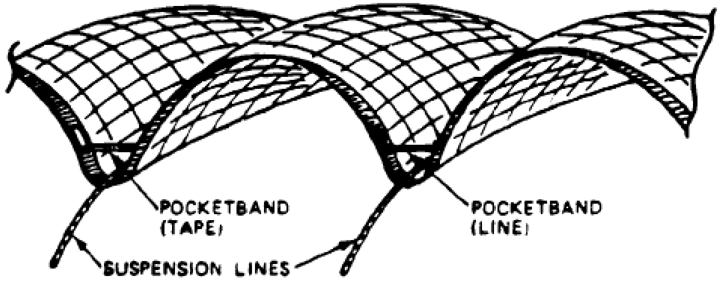
- Fixed length to reef parachute at certain diameter
- Cylindrical cordage

Suspension Lines

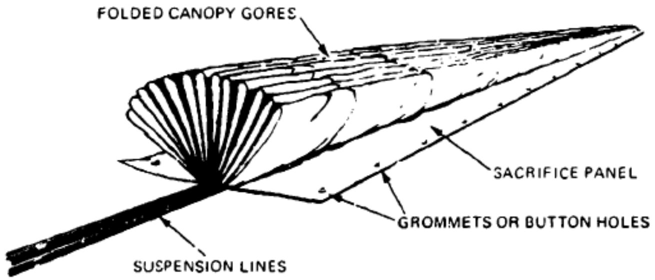
- Continuous line from riser, through canopy and back
- Cylindrical cordage

Riser

- Attaches parachute to payload
- Cylindrical cordage or flat straps



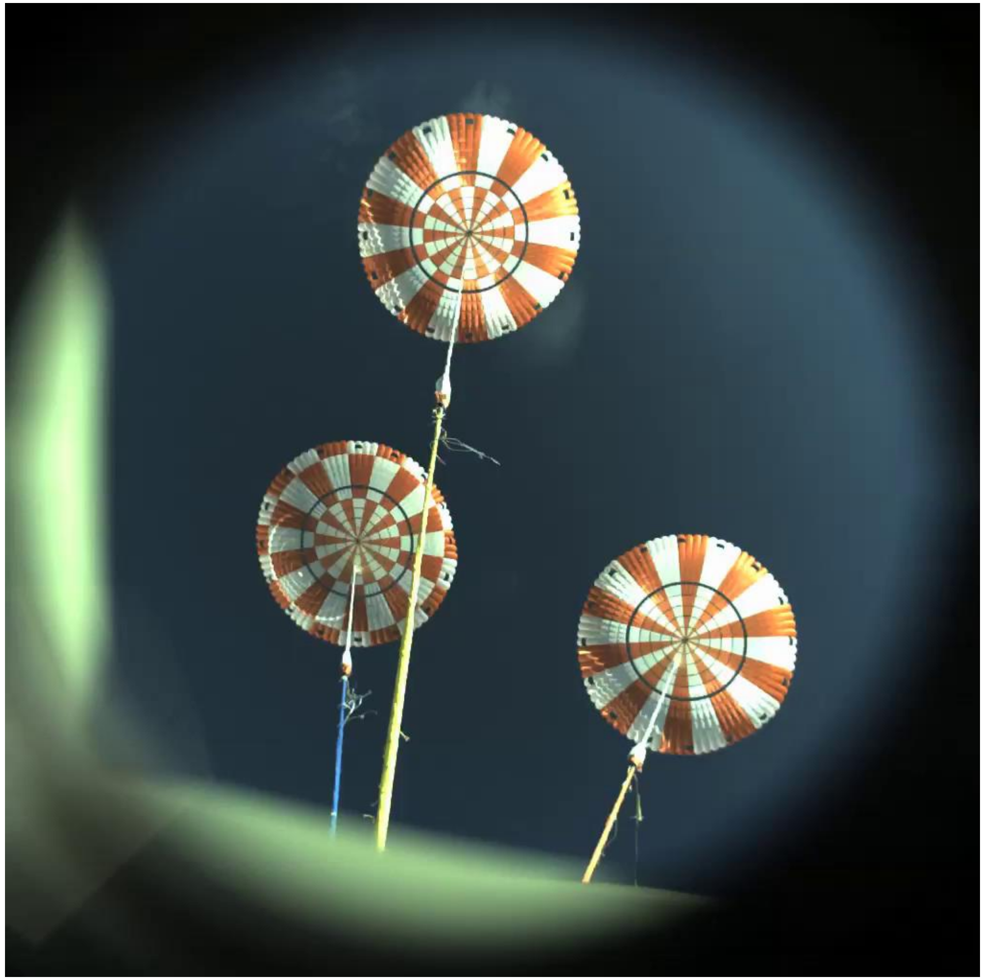
Canopy Detail (T.W. Knacke)



Canopy Folding/Packing Detail (T.W. Knacke)

Parachute Strain Measurements

- Parachutes are designed and analyzed with simulations and math models, mostly dealing with aerodynamics of flight
- Models are verified by tests, primarily using video analysis
- Strain and tension monitoring systems are desired to verify the performance of the structural system
  - In-line systems have been used with mixed results that require modification to existing structure
  - New systems are desired that do not require modification of the parachute lines
- Three main material types used in the structure call for technically distinct strain measurement devices:
  - Broadcloth/woven fabric
  - Cordage/rope
  - Strap/flat woven fabric



Orion Parachute Deployment on EFT-1

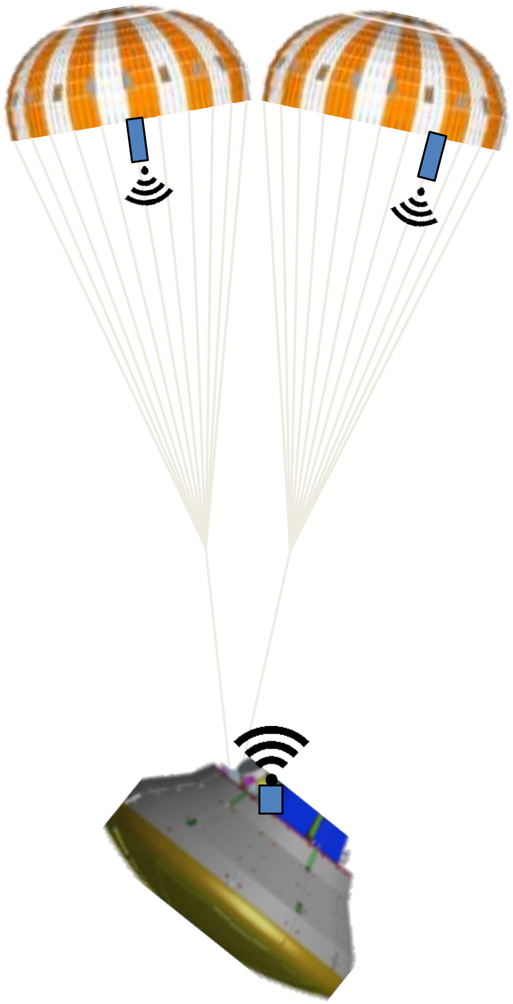
Parachute Canopy Instrumentation Platform

- Parachute Canopy Instrumentation Platform (PCIP)
  - JSC R&D funded initiative to establish 2-way communication with parachute canopy
  - **Includes development and integration of textile-mounted sensors** and RF electronics

- Project Goals
  1. Demonstrate 2-way communication between payload and canopy
  2. Collect in-flight reefing line tension
  3. Demonstrate wirelessly activated reefing line cutter in flight

- Structural engineering role: **Develop strain gauges to measure tension in cordage and strain in canopy**
  - Reefing line tension
  - Riser line tension
  - Suspension line tension
  - Canopy surface strain

(Reefing, riser and suspension line tension: Cordage systems)

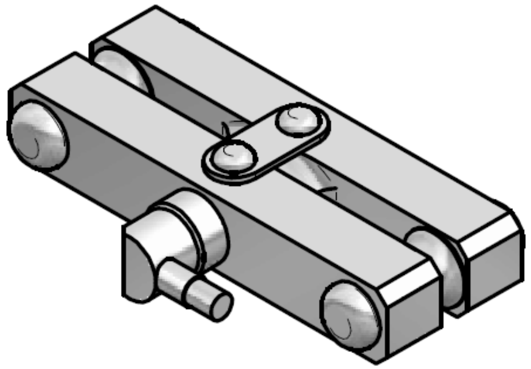


PCIP Load Cells

- Concept based on seat belt tension measurement device and HIAD strap tension device
- Custom designed and manufactured by Novatech Measurements Ltd
- Cord takes takes load uniaxially through the length of the material
- Load cell is a three-point bend device
  - As cord is loaded, it imparts a bending onto the load cell
  - Four strain gauges, in a full Wheatstone bridge, on the load cell measure the amount of bending, which is translated to the tension in the cord via calibration

HIAD Strap Tension Device

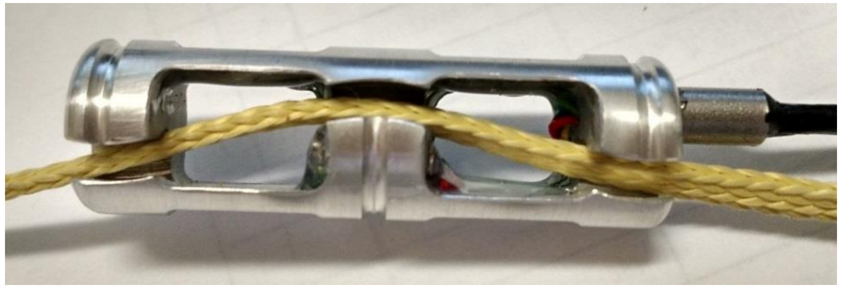
Reefing Line Tension Load Cell v1



(Credit: Novatech Ltd.)

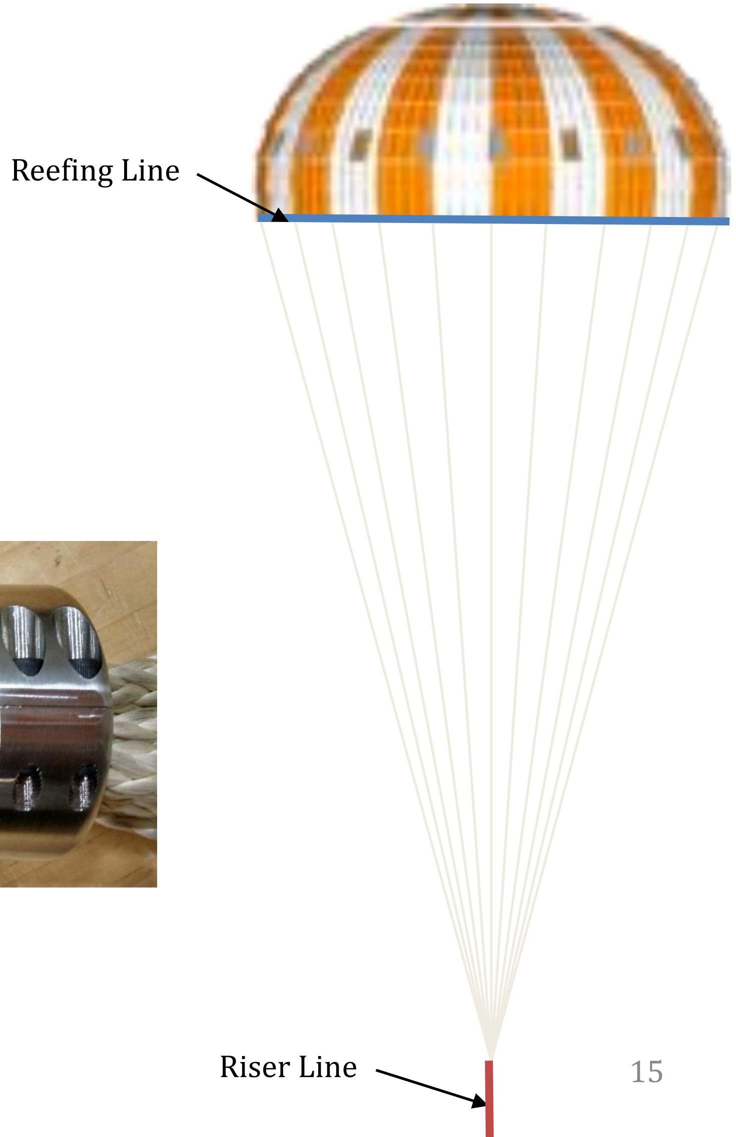
PCIP Load Cells

- Modified the design to minimize interference and remove sharp edges
- Extended design to multiple locations on parachute
  - Reefing line
  - Riser line
- Design assumptions
  - Assume cord takes load uniaxially and independent of orientation
  - No normal force on the load cell (cordage is loaded without any pressure wall pushing against it)
  - Device must be able to be installed in middle of cord, without access to ends



Reefing Line Load Cell
Approx. 3” length

Riser Line Load Cell
Approx. 6” length



PCIP Load Cells Flight Tests

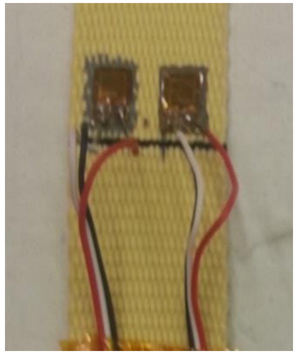
- Riser load cells were used on CPAS CDT-16 drop test in August 2015
  - Successfully measured riser tension throughout entire parachute sequence
  - Endured loads and dynamics of deployment and landing with no visible damage
- Reefing line load cell used on sub-scale drop test in July 2016
  - Successfully measured reefing line tension through two reefing stages
  - Endured packaging, deployment and landing loads
- Upcoming flights:
  - Reefing line load cell on sub-scale test (Sep 2016)
  - Reefing line load cell on CPAS Qualification test (Feb 2017)

All three main riser load cells still attached (shown wrapped in white), following the CPAS drop test (Image credit: Yuma Sun)

Canopy Strain Gage Concepts

- Canopy strain gage devices need strong adhesion to fabric and maximum flexibility
- Currently evaluating commercial-off-the-shelf (COTS) products for strain measurement
- Based on resistive strain gauges – product changes resistance as material is stretched

Traditional Strain Gage



- Provides reliability of traditional strain gauge
- Needs proper adhesion to surface of material that transfers strain without loss

Coverstitch

- Fully integrated system build into the material at a base level
- Provides good gross tension measurement

Conductive Paint

- Painted onto surface of material
- Can be used in various shapes/patterns and can cover variety of materials and surfaces

Conductive RTV

- Painted onto surface of material
- Can be used in various shapes/patterns and can cover variety of materials and surfaces

Metal Rubber Conductive Material

- Unique material provides deformation of 200%
- Requires proper adhesion to surface of material

StretchSense

- Capacitance based stretch sensor
- Equipped with Bluetooth wireless technology and smartphone data acquisition app
- Fabric sensor can be sewn into surface of material

Testing in progress…

Summary

- Strain measurement systems for fabric structures need to be developed
  - Required for ground testing and flight certification
  - Needed for long term structural health monitoring
- Current methods use optical measurements or heritage strain gage systems
- PCIP has developed load cell devices for cordage systems to be used on parachute testing and development
- Future work to develop and test canopy strain gauges
- Parachute work translates directly to development of structural health monitoring for inflatable structures
- **End goal is to have a reliable and standard suite of strain measurement devices for fabric based structures that can be used both on the ground and in space, providing valuable data for future lightweight structures**

QUESTIONS?